



The Climate Change and Carbon Management (CC&CM) program is a growing interdisciplinary research effort within ESD. The program conducts research to increase the scientific foundation for climate change prediction, impact assessment, and mitigation. In addition, program research on biogeochemical cycles and climate addresses other pressing issues under the purview of DOE and other public agencies, such as stewardship of water resources and the environmental effects of energy and land use. To that end, we have active projects on climate and hydrology, climate change, terrestrial and marine biogeochemistry, and carbon management in geologic, oceanic, and terrestrial systems.

One of CC&CM's strengths is its active partnerships with universities, industry, and other research laboratories. The most important of these is our strong partnership with UC Berkeley, which includes collaboration with faculty, sharing research facilities, teaching, advising and mentoring UC students, and interaction with the Berkeley Atmospheric Sciences Center.

RECENT ACCOMPLISHMENTS

Below we illustrate some of the recent accomplishments of CC&CM in the areas of climate studies, terrestrial carbon cycling, oceanic carbon cycling, and carbon capture and storage in geologic reservoirs.

Coupled Climate Carbon Cycle Modeling

A major concern about future climate forcing is how the current terrestrial and marine carbon sinks will respond as fossil fuel emissions increase and climate changes. ESD scientist Inez Fung and co-workers recently added interactive land and ocean carbon cycles to the global Community Climate Simulation Model (CCSM) to study how diverse features of the environment, including plants, soil, precipitation, microbes, oceans, phytoplankton, clouds, and carbon dioxide emissions interact to affect the strength of carbon sinks. They found an inverse relationship between fossil fuel emission rates and land and ocean carbon sink capacity—the faster the emission, the less effective the carbon sinks. This result implies that carbon storage by the oceans and land will



Research Program

CLIMATE CHANGE AND CARBON MANAGEMENT

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lag further and further behind, and climate warming will accelerate with growing carbon dioxide emissions. Climate warming will increase the amount of carbon dioxide in the atmosphere, which in turn makes the climate even warmer, and so on. This model and nine others in a coupled climate carbon cycle model intercomparison (C4MIP) predicted large decreases in ecosystem carbon uptake (especially in the tropics) with climate change, and consequently an acceleration of warming.

Regional Climate and Water Resources

Climate Change and Carbon Management scientists contributed to the Fourth Assessment Report of the Intergovernmental Panel for Climate Change through the above work and through regional climate analysis. The Fourth Assessment Report includes CC&CM's analyses of regional climate model projections, temperature extremes, and the impacts of snowpack on water resources. CC&CM researchers quantified the range of uncertainty in the hydrologic response, finding that, regardless of emissions scenario, there are likely to be significant decreases in snowpack and available water resources in California. This finding has led CC&CM researchers to develop a new water-energy model with surface water, groundwater, and dynamic vegetation, and to apply this to a multidecade drought study. They have determined new heat extreme likelihoods based on exceedence probability analysis, and determined the intensity and persistence of these heat extremes. Correlating these results with temperature-related energy demand suggests that current energy capacity projections will likely be exceeded. Additional recent activities include a regional climate model intercomparison that evaluated California land-use change between pre-industrial and present time, multidecadal high-resolution simulation of land-surface processes with the development of scaling relationships for soil moisture, an analysis of the impact of China's Three Gorges Dam on the local climate, an analysis of the relationship between atmospheric circulation and snowpack in the western U.S., heat island effects in California's Central Valley, climate change water allocation sensitivities, and new ensemble simulations for the initialization of soil moisture and plant functional types.

Ocean Carbon Cycle

Oceans contain more carbon than any other dynamic reservoir on earth. They pose a great observational challenge because the

pulses of biological productivity are episodic and rapid, and the areas are vast. Climate Change and Carbon Management scientists have developed the Carbon Explorer, an autonomous float that uses satellite telemetry to report its observations from distant oceans. Twelve of these low cost robots have achieved the equivalent of 8 years of continuous observations of particulate organic carbon variability in remote and biologically dynamic ocean regions since 2001, a data record that would not have been possible with conventional research ships. Seagoing work to prove and enhance new sensors for the Carbon Explorer is ongoing. CC&CM's new sensor for particulate inorganic carbon was operationally deployed to full ocean depth during pole-to-pole survey transects of the Atlantic Ocean in July 2003 and January 2005. The data it reported allow the first comprehensive examination of the spatial variability of particulate organic and inorganic carbon. CC&CM's optical carbon sedimentation recorder was most recently deployed in Oyashio waters near Japan.

Terrestrial and Atmospheric Carbon Cycle

One of the focal points of carbon cycle research is the vast range of scales—from a single leaf to an entire continent—that must be bridged with measurements and models. The Climate Change and Carbon Management program has implemented a coordinated suite of carbon concentration, isotope, and flux measurements in the Southern Great Plains, as part of the DOE Atmospheric Radiation Measurement (ARM) Program. Simultaneously monitoring from crop fields, tall towers, and aircraft, this facility is one of the best-instrumented site for regional carbon studies in the world. To support the North American Carbon Program, various approaches to estimating regional scale ecosystem CO₂ fluxes are under way.

The second major thrust in this area is determining terrestrial carbon residence times and storage strategies. Soils contain twice as much carbon as the atmosphere and efflux carbon at ten times the rate of fossil fuel emissions. CC&CM scientists are using ecosystem experiments and isotopic analysis to study the rates of C cycling and storage belowground. Results from this work are leading to changes in forest ecosystem models and estimates of the amount of carbon pumped belowground by root growth.

CC&CM has recently begun a new project exploring the impact of climate change on ecosystems: "An Annual Grassland Exploration of Scaling from Genomes to Ecosystem Function." This effort tests whether we can enhance our ability to predict ecosystem response to future environmental conditions by incorporating genomic, transcriptomic, and bioinformatics analysis with traditional biogeochemical and physiology approaches.

Carbon Capture and Storage

Carbon dioxide capture with storage in deep geological formations is one of the most promising options for mitigating CO₂ emissions over the next century. DOE began funding ESD research and

development in 2000, to develop greater understanding of storage processes and security through the application of high-resolution monitoring tools to field-scale pilot and industrial scale projects.

CC&CM scientists are playing a leading role in WESTCARB (the West Coast Regional Sequestration Partnership). This is one of seven partnerships recently established by the DOE-Fossil Energy to evaluate CO₂ capture, transport, and sequestration technologies best suited for different regions of the country. A number of major tasks have already been completed within this partnership, including the identification of major CO₂ point sources and transportation options, an assessment of the ability for geologic sinks in the West Coast region to store CO₂, development of monitoring approaches and screening criteria for comparing storage sites, and identification of sites and industry partners for three pilot tests in California and Oregon to be conducted over the next four years.

Also, over the past year, CC&CM scientists have lead the way in designing and monitoring the first U.S. pilot test of CO₂ storage in a deep saline formation on the Texas Gulf Coast. The test involved injecting 1,600 tons of CO₂ into highly permeable sandstone 1,540 m below the ground surface. Combined seismic imaging, pressure monitoring, and fluid sampling successfully tracked migration of the injected CO₂ and demonstrated that its movement was consistent with model predictions. As part of this work, CC&CM researchers developed a novel U-tube sampler for rapid sampling of formation fluids under *in situ* pressure conditions, to monitor CO₂ arrival at the observation well. They also demonstrated the use of crosswell seismic methods to image CO₂ in the subsurface.

In addition, CC&CM began participation in a new research program on geologic CO₂ storage, the Zero-Emission Research and Technology Program (ZERT), which aims to generate the fundamental understanding necessary for predicting long-term performance of geological storage and selecting secure storage sites. For ZERT, CC&CM is developing reliable techniques to predict CO₂ migration and trapping mechanisms, demonstrating storage effectiveness, and quantifying migration out of the storage formation and release rates at the surface. A combination of laboratory, field, theoretical and simulation studies are being used to accomplish these goals.

Funding and Partnerships

The Climate Change and Carbon Management Program is funded by a variety of federal and state agencies, and international collaborations. These include the U.S. Department of Energy's Office of Basic Energy Sciences, Office of Fossil Energy, Office of Geological and Environmental Research, and Office of Biological and Environmental Research; National Aeronautics and Space Administration; National Science Foundation; National Oceanographic and Atmospheric Administration, as well as the California Energy Commission and CAL-FED.

FLOW MODELING OF SUPERCRITICAL CO₂ INJECTION AT THE FRIO BRINE PILOT

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RESEARCH OBJECTIVES

Geologic sequestration of CO₂ in brine-bearing formations has been proposed as a means of reducing the atmospheric load of greenhouse gases. Numerous brine-bearing formations have been identified as having potential for geologic sequestration of CO₂. One promising setting is the fluvial/deltaic Frio formation in the upper Texas Gulf Coast, which was the site of a CO₂ sequestration pilot in October 2004. The objective of this research was to investigate the physical processes controlling the behavior of CO₂ in the subsurface during the pilot, by means of numerical modeling. Sensitivity simulations were conducted to help design the pilot, predictive simulations were used to assess our state of understanding of the issues accompanying CO₂ sequestration in brine-bearing formations, and calibration simulation results were compared to results of the pilot to improve that understanding.

APPROACH

The numerical simulator TOUGH2, developed at Berkeley Lab, is used to model the flow and transport processes occurring during the Frio Brine Pilot. TOUGH2 considers all flow and transport processes relevant for a two-phase (liquid-gas), three-component (CO₂, water, dissolved NaCl) system. In the subsurface, supercritical CO₂ forms an immiscible gas-like phase and partially dissolves in the brine. Under the pilot conditions ($P = 150$ bars, $T = 55^\circ\text{C}$, $\sim 100,000$ ppm salinity), supercritical CO₂ is strongly buoyant compared to the native brine.

A three-dimensional numerical model of the pilot site was developed over the months preceding CO₂ injection, beginning with a simple model, and adding more detail and realism as results of site characterization studies became available. The final model consists of 23 m thick brine-saturated sand near the top of the Frio within a 900 m x 900 m partially sealed, dipping fault block. Two wells penetrate the sand, one injection well and one observation well, both of which are perforated over the upper quarter of the sand thickness.

ACCOMPLISHMENTS

Sensitivity modeling helped decide practical questions such as which of several upper Frio sands to inject into, how far apart the injection and observation wells should be (in particular showing that existing wells were too far apart, necessitating the drilling of a new injection well), how much CO₂ to inject and at what rate.

Modeling of hydrologic tests helped in the design of pre-injection, site characterization pump and tracer tests to optimize the information gained on formation flow properties, *in situ* phase conditions, and fault-block boundary conditions. Predictive modeling of CO₂ movement between wells (Figure 1 and Table 1) has illustrated the complex interplay between phase interference and buoyancy flow that occurs as CO₂ is injected into a high-permeability, steeply dipping sand layer, and the ability of the model to reproduce it. By running simulations with a range of parameters and comparing model results to field data, we have greatly improved our understanding of these flow processes. Generally good agreement between observed and modeled CO₂ and tracer travel times between injection and observation wells has validated our ability to model CO₂ injection, while minor discrepancies have pointed out areas where future research is needed.

Table 1. Comparison of observed and modeled CO₂ arrivals at the observation well

	Event	Time (days)
Field	Immiscible CO ₂ arrival at observation well	2.1
Model	Dissolved CO ₂ arrival at observation well	2.8
	Immiscible CO ₂ arrival at observation well	3.0

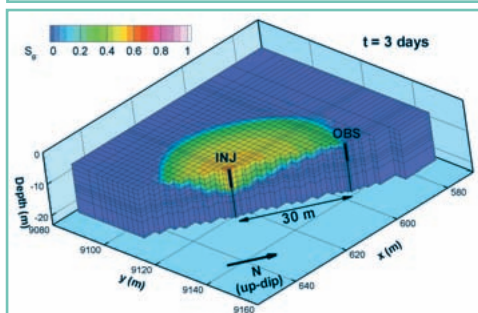


Figure 1. Modeled distribution of CO₂ in the immiscible gas-like phase after 3 days of injection at the Frio Brine Pilot, where CO₂ was injected at an average rate of 180 metric tons per day for nine days. The injection and observation wells are displayed as black lines, with the perforated intervals shown thicker.

SIGNIFICANCE OF FINDINGS

This work has demonstrated that we have a good understanding of the complex multiphase flow processes involved in CO₂ injection, as well as an effective modeling capability for designing future CO₂ injection tests and investigating CO₂ sequestration scenarios.

RELATED PUBLICATION

Doughty, C., and K. Pruess, Modeling supercritical CO₂ injection in heterogeneous porous media. *Vadose Zone Journal*, 3(3), 837-847, 2004. Berkeley Lab Report LBNL-52527.

RELATED WEBSITE

<http://www-esd.lbl.gov/GEOSEQ/index.html>

ACKNOWLEDGMENTS

This work is part of the GEO-SEQ project, which is supported by the Assistant Secretary for Fossil Energy, Office of Sequestration, Hydrogen, and Clean Fuels, through the National Energy Technology Laboratory, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

THE U-TUBE: AN INNOVATIVE METHOD FOR COLLECTING AND ANALYZING DEEP-WELL SAMPLES

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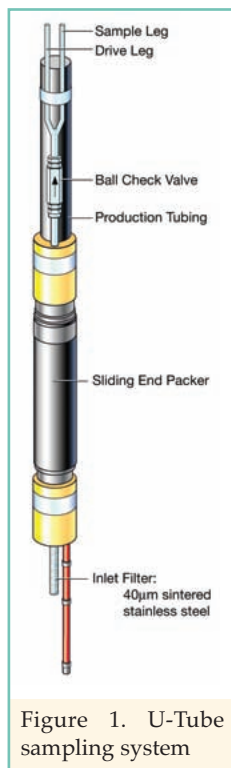
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RESEARCH OBJECTIVES

A novel sampling system, called a “U-tube,” was deployed at the Frio Project site (Dayton, Texas) to collect and analyze multiphase fluids from a 1.5 km deep well during a CO₂ injection experiment, performed on a brine-saturated reservoir. Collection of representative fluid samples from deep reservoirs is challenging, because samples undergo depressurization and can be contaminated when brought to the land surface, causing changes in fluid chemistry, physical properties, and exsolution of dissolved gases. Project-specific goals also required high-frequency sample collection to capture CO₂ breakthrough and to characterize rapidly changing brine-CO₂ saturations during injection. High-quality samples and fluid saturation measurements provide insight into geochemical and hydrologic processes affecting sequestration of greenhouse gases (including CO₂) in deep geologic formations.

APPROACH

The U-tube sampling system consists of a continuous loop of steel tubing that starts and ends at land surface and is strapped to the outside of standard oil-field production tubing lowered into the well (Figure 1). The bottom of the U-tube is installed above the perforated production (sampling) interval and an inflatable packer. The packer isolates the interval from the upper part of the well, thus minimizing the volume purged during sample collection. A check valve connected to the bottom of the U, located immediately above the packer, controls the movement of fluid from the production interval into the U-tube. A short tube passing through the packer connects the U-tube through a filter to the production interval. The filter allows formation water to enter the U-tube, but prevents debris from clogging the valve. Operation of the U-tube is relatively simple. Compressed nitrogen gas is injected into the “drive



leg” of the U-tube, closing the downhole check valve and forcing a slug of fluid to the surface via the “sample leg.”

ACCOMPLISHMENTS

While the basic premise underlying the U-tube is not new, the system is unique because careful attention was given to processing the recovered two-phase samples. Strain gages mounted beneath high-pressure sample vessels at the surface measure the ratio of recovered brine to supercritical CO₂, providing gas-brine densities at reservoir conditions. A quadrupole mass spectrometer provided real-time gas analyses, allowing measurement of CO₂ and tracer breakthrough, and providing information on CO₂ saturations.

SIGNIFICANCE OF FINDINGS

Conventional approaches for deep-well sampling use submersible pumps, gas lift, or surface-based wireline samplers. Submersible pumps and gas-lift techniques can degas and/or contaminate samples, thus compromising fluid chemistry and promoting phase separation. Wireline samplers take small, discrete, infrequent samples that have the potential to miss CO₂ breakthrough. In comparison, the U-tube sampling system can be used to collect frequent, representative samples at reservoir conditions. In addition, it easily incorporates other program elements into its design, including bottomhole pressure and temperature measurements, and wireline logging through the center production tube.

RELATED PUBLICATIONS

Freifeld, B.M., C.A. Doughty, R.C. Trautz, S. Hovorka, L.R. Myer, and S.M. Benson, The Frio Brine Pilot CO₂ Sequestration Test—Comparison of field data and predicted results. Chapman Conference on the Science and Technology of Carbon Sequestration, San Diego, California, January 16–20, 2005. Berkeley Lab Report LBNL-56649.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary of the Office of Fossil Energy, U.S. Department of Energy, National Energy Technology Laboratory, under Contract No. DE-AC03-76SF00098.

COUPLING OF CLM3 INTO MM5 TO IMPROVE SNOW AND DYNAMIC VEGETATION PROCESSES

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RESEARCH OBJECTIVES

The Pennsylvania State University / National Center for Atmospheric Research (Penn State/ NCAR) fifth-generation Mesoscale Model (MM5) has been extensively used for regional weather and climate forecasts as well as research for more than ten years. However, the snow schemes in this model are unable to produce realistic simulations for the winter and spring periods because of oversimplified snow physics (Jin and Miller, 2005a). Additionally, the prescribed vegetation parameters, such as leaf area index, significantly weaken the model's ability to predict future climate and weather. In this study, the advanced NCAR Community Land Model version 3 (CLM3), with its sophisticated snow and dynamic vegetation schemes, is incorporated into MM5 to improve its forecast and simulation capability.

APPROACH

The nonhydrostatic version of MM5 is used in this study, with the Grell convection scheme adopted to parameterize cumulus clouds and the Medium Range Forecast planetary-boundary-layer scheme applied to solve boundary-layer processes. CLM3 physically describes the mass and heat transfer within the snow-pack, using five snow layers that include liquid water and solid ice. Interactions among the snow, soil, and vegetation are a function of the CLM3 mass and energy equations. A sophisticated surface albedo scheme is chosen to improve the surface energy-balance simulations. Introduction of a maximum of eight subcells within each CLM3 cell strengthens the description of land-surface heterogeneity. The vegetation is dynamically generated under soil and atmospheric conditions favoring vegetation respiration and photosynthesis processes.

The coupled MM5-CLM3 was used to generate two-way, 60-km-to-20-km-resolution nested simulations. The 20 km simulation is the focus of the present analysis. The National Centers for Environmental Prediction (NCEP) Reanalysis data was used as MM5-CLM3 initial and 6-hourly-updated lateral-boundary conditions for the period of March 1 to May 31, 2002, and the model output was saved every six hours. The MM5-CLM3 performance was evaluated at the Columbia River basin for the cold season, using ground observations from an automated Snowpack Telemetry (SNOTEL) system. The SNOTEL

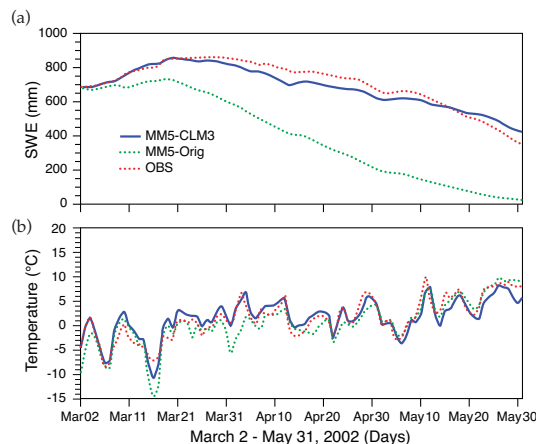


Figure 1. Comparison of simulated and observed (a) SWEs and (b) temperatures averaged over 50 SNOTEL stations in the Columbia River basin for the period of March 2 through May 3, 2002.

data includes snow-water equivalent and surface air temperature.

ACCOMPLISHMENTS

Compared with the original version of MM5, the coupled MM5-CLM3 significantly improves snow and surface temperature simulations. Figure 1a shows the time series of snow-water equivalent (SWE) averaged over 50 SNOTEL stations in the Columbia River basin. The SWEs produced by MM5-CLM3 are in very good agreement with the observations, as a result of sophisticated snow physics and related model processes, while the SWEs from the original MM5 with simple snow processes are greatly underestimated. The 50-station averaged

temperatures from MM5-CLM3 are also consistent with observations, but the original MM5 produces cold biases during the early simulation period, caused by the large amount of energy consumed by the faster snow melt.

SIGNIFICANCE OF FINDINGS

The coupled MM5 and CLM3 model significantly improves snow and surface air-temperature simulations. The evaluation of the dynamic vegetation scheme, using our ensemble techniques, are part of our current work and will be reported in the near future. This coupled model increases the predictability of the regional climate model and provides a reliable tool for regional weather and climate research.

RELATED PUBLICATIONS

Jin, J., and N.L. Miller, An analysis of climate variability and snowmelt mechanisms in mountainous regions. *Journal of Hydrometeorology* (in press), 2005a. Berkeley Lab Report LBNL-53845.

Jin, J., and N.L. Miller, Coupling of CLM3 into MM5 to improve snow simulation and dynamic vegetation processes. *Journal of Hydrometeorology* (submitted), 2005b.

ACKNOWLEDGMENTS

This work was supported by Laboratory Directed Research and Development (LDRD) funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

RELATIONSHIP BETWEEN ATMOSPHERIC CIRCULATION AND SNOWPACK IN THE WESTERN UNITED STATES

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RESEARCH OBJECTIVES

Snow anomalies in the western United States (WUS) have been widely investigated by many researchers because of their significant impact on water availability. This previous research indicated that the ocean has a dominant effect on snow variation in the WUS and contributes to more than 60% of the variance in snow anomalies. This study investigates those findings, focusing on the snow variations in the WUS resulting from anomalous atmospheric circulation, attributed to both atmospheric internal variability and tropical Pacific sea surface temperature (SST) forcing.

APPROACH

In this study, the observed Snow Water Equivalent (SWE) data in the WUS was obtained from snow course data collected manually by the U.S. Department of Agriculture (USDA) cooperative snow survey program and the California Department of Water Resources. The April 1 SWE maximum for 1950–1997 is the focus of this analysis. The observed tropical Pacific SST was averaged for December to February (DJF) to identify winter season El Niño-Southern Oscillation (ENSO) events. When the average SST is above 1°C, below -1°C, or between -1°C and 1°C, the ENSO event is defined as “warm,” “cold,” or “neutral,” respectively. For 1950–1997, there are 8 warm, 6 cold, and 33 neutral winters. The Pacific/North American (PNA) index indicates the 500 mb geopotential height anomalies. PNA indices for DJF are averaged to identify winter PNA patterns. When the DJF-average PNA index is above 0.5, the corresponding atmospheric pattern is defined as the “positive PNA pattern”; when it is below -0.5, the atmospheric pattern is defined as the “negative PNA pattern.” There are 9 positive and 6 negative PNA patterns for the 33 neutral winters.

ACCOMPLISHMENTS

Table 1 provides the quantitative comparison of SWE, temperature, and precipitation anomalies during the ENSO episodes and under the PNA circulation patterns, which represent the ocean and atmospheric internal variability influences, respectively. The numbers for the SWE anomaly in Table 1 are the averages of those SWEs passing the 95% significance test in the northwest and southwest, and the numbers for temperature and precipitation anomalies are the averages over the corresponding snow-course stations in the same regions. Table 1 shows that the warm ENSO generates a significant positive SWE anomaly in the southwest

(55.2 mm), but has a weaker impact on the northwest SWE (-3.7 mm). The cold ENSO produces a strong positive SWE anomaly in the northwest (117.8 mm), but has a mild effect on the southwest SWE (-21.5 mm). Under the positive PNA pattern without oceanic forcing, the entire WUS has negative SWE anomalies (-80.2 mm in the northwest and -71.2 mm in the southwest), while under the negative PNA pattern, the WUS has positive SWE anomalies (73.1 mm in the northwest and 88.8 mm in the southwest). Table 1 also indicates that the positive SWE anomaly results from the stronger precipitation and colder temperature, whereas the negative SWE anomaly is caused by weaker precipitation and warmer temperature. The empirical orthogonal function (EOF) analysis further shows that the PNA patterns contribute to 39% of the total SWE variance, and the ENSO episodes account for only 18%, indicating that the atmospheric internal variability has a dominant impact on the SWE variations in the WUS.

Regions Events	Northwest			Southwest		
	SWE(mm)	P(mm)	T(°C)	SWE(mm)	P(mm)	T(°C)
Warm ENSO	-21.5	-11.0	0.52	55.2	32.7	-0.14
Cold ENSO	117.8	44.7	-0.81	-3.7	-3.1	-0.28
Positive PNA	-80.2	-22.6	0.77	-71.2	-27.2	0.69
Negative PNA	73.1	20.5	-1.09	88.8	26.6	-0.56

Table 1. SWE, temperature, and precipitation anomalies averaged over the snow course stations, where the SWEs pass the 95% Student's *t* test (P is precipitation and T is temperature)

SIGNIFICANCE OF FINDINGS

Our study shows that the oceanic impact on WUS snow is likely overestimated, and that atmospheric internal variability also plays an important role in WUS snow volume. This study provides significant insight into forecasts of winter and spring snow mass in the WUS, where snow is the major water resource.

RELATED PUBLICATIONS

Jin, J., N.L. Miller, S. Sorooshian, and X. Gao, Relationship between atmospheric circulation and snowpack in the western United States. Hydrological Processes (in press), 2005. Berkeley Lab Report LBNL-55404.

ACKNOWLEDGMENTS

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DEVELOPMENT OF A COUPLED LAND SURFACE AND GROUNDWATER MODEL

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RESEARCH OBJECTIVES

Land-Surface Models (LSM), used for numerical weather simulation, climate projection, and as inputs to water management decisions, do not treat the LSM lower boundary in a fully process-based fashion. This lower boundary is often assumed to be zero flux, or the soil moisture content is set to a constant—an approach that while mass conservative, ignores processes that alter surface fluxes and water quantity and quality. Conversely, groundwater models (GWM) for saturated and unsaturated flow often have overly simplified upper-boundary conditions that ignore soil heating, runoff, snow, and root-zone uptake. The objectives of this study are to indicate a new approach and methodology for coupling a state-of-the-art CLM (Common Land Model) and a variably saturated GWM (ParFlow), and to replicate this study for CLM and the Berkeley Lab Earth Sciences Division GWM, TOUGH2.

APPROACH

The water-balance equations represent the link between the LSM and the GWM. The CLM and ParFlow models were coupled at the land surface and soil column by replacing the soil column/root zone soil moisture formulation in CLM with the ParFlow formulation. All processes within CLM, except for those that predict soil moisture, are preserved within the original CLM equations.

The coupled model, CLM.PF, communicates over the 10 soil layers in CLM, with the uppermost cell layer in ParFlow. Soil saturation is calculated from the hydraulic pressure solution over the entire domain, with the water content at the upper ten layers passed back to CLM, where soil surface temperatures, heat fluxes, and energy balances are calculated.

ACCOMPLISHMENTS

Simulations for both the coupled (CLM.PF) and uncoupled (CLM) models are compared to the Usad Watershed observations. The simulations of sensible heat flux and evapotranspiration for the coupled and uncoupled models agree closely. However, the runoff rates are more accurately simulated by the coupled model, with the uncoupled model tending to underestimate the observed flow rate. The differences in runoff result from the explicit simulation of the water table (WT) in the coupled model.

The three plots of soil saturation provide insight into the differences in model simulation

and agreement with observations. Shallow simulations (20 cm) show that soil saturation for the coupled and uncoupled models are very similar, particularly during the summer months. This corresponds to the similarities in the simulated evapotranspiration between the two models. Deeper simulations of soil saturation (40 cm and greater) are quite different; with the coupled model agreeing well with observations (see Figure 1). CLM.PF stores water in the subsurface, and includes a memory effect on model behavior that extends beyond seasonal time cycles. This effect can be seen in the figure, where WT storage and soil moisture memory affect other modeled processes.

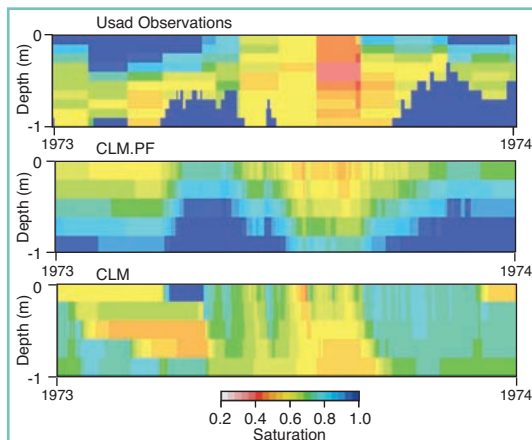


Figure 1. Plot of observed and simulated soil saturations for Valdai as a function of time and depth for 1973. Average soil moisture observations for the Usad catchment are plotted in the first panel, with CLM.PF model simulations in the middle and CLM simulations at the bottom. Note that only the first 1 m of model simulations are plotted to match the observations. Note also that the solid blue regions denote completely saturated conditions where the WT depth is less than one meter.

SIGNIFICANCE OF FINDINGS

CLM.PF behaves much differently from CLM and expands the capabilities of the groundwater model to include land surface processes. CLM.PF provides simulations of the subsurface, which, because of the explicit accounting for water up to and below the WT,

have a memory of water stored in the deep subsurface. The simulations presented here show that this scheme balances mass across the land surface/groundwater boundary and provides new insights into coupled processes. The coupled model also has a different depiction of the root-zone soil moisture than the uncoupled model, leading to more realistic behavior that more closely matches observations at the Usad site. The coupled model demonstrates the need for better groundwater representation in land surface schemes. This study has been duplicated for CLM and TOUGH2 with similar results, and we expect to use this for new applications.

RELATED PUBLICATION

Maxwell, R.M., and N.L. Miller, Development of a coupled land surface and groundwater model. *Journal of Hydrometeorology*, 6 (3), 233–247, 2005. Berkeley Lab Report LBNL-55029.

ACKNOWLEDGMENTS

This work was conducted under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48, and Berkeley Lab under the DOE Fossil Energy Environmental Program, Contract No. DE-AC03-76F00098.

THE DOE WATER CYCLE PILOT STUDY: MODELING AND ANALYSIS OF SEASONAL AND EVENT VARIABILITY AT THE WALNUT RIVER WATERSHED

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RESEARCH OBJECTIVES

The DOE Water Cycle Pilot Study represents a successful multi-laboratory investigation to better understand water cycle variability—by evaluating DOE climate models, developing water isotopic data to constrain such climate models, and to test process descriptions and their sensitivity at multiple scales. The research objectives are to: (1) evaluate predictions of components of the water budget, using a set of nested models with different spatial resolutions, along with archived and new field data from the Walnut River Watershed (WRW); (2) evaluate multiscale water isotope modeling as a means of tracing sources and sinks within and external to the WRW and the Atmospheric and Radiation Measurements Program-Southern Great Plains (ARM SGP) site; (3) identify water-budget-model improvements and data needs over a range of scales. The DOE Water Cycle Pilot was funded for two years by DOE's Office of Basic Energy Research (BER), and resulted in several follow-on studies, including a paper by Sharif et al. (2005) on a 51-year simulation and derivation of scaling relationships for the Red-Arkansas River Basin.

APPROACH

Water isotopic measurements of precipitation, surface water, soils, plants, and atmospheric water vapor were collected every three months and during the DOE Intensive Observing Period, April 1 to June 30, 2002. Land-surface modeling compared 1 km fluxes for different modes and for a 51-year simulation. Different wetting and drying conditions caused by different controls were investigated. Multi-scale atmospheric simulations using the MM5 and radar-based data have been analyzed and are discussed below (Miller et al., 2005).

ACCOMPLISHMENTS

It was shown that isotopic sampling of rivers and lakes provides a good long-term average of precipitation patterns and helps to validate water cycle simulations in regional climate models, such as MM5. Analysis of the simulated MM5 6-hour precipitation and radar-derived precipitation has indicated that MM5 slightly underestimates at a 4 km resolution and lags behind the radar-precipitation onset. MM5 exhibits strong capabilities in predicting precipitation occurrences, with somewhat less accuracy in predicting precipitation amounts.

The TOPLATS land surface model was evaluated for a number of scenarios, resolutions, and periods. Eleven simulations were performed with different modes, with several variations in the representations of spatial variability of precipitation, land use, topography, and soils—to assess the sensitivity of the model

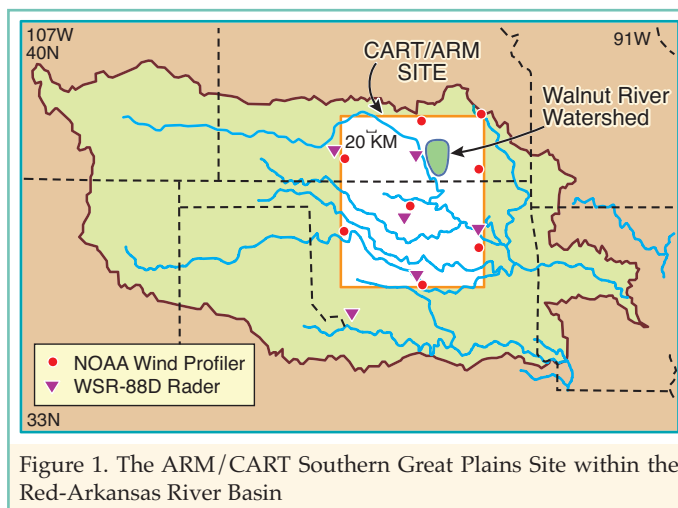


Figure 1. The ARM/CART Southern Great Plains Site within the Red-Arkansas River Basin

response. Model results suggest that in parts of the catchment, evapotranspiration switched between being atmospherically controlled to soil-moisture controlled.

SIGNIFICANCE OF FINDINGS

The DOE WaterCycle Pilot Study resulted in a number of findings that are highlighted in Miller et al. (2005b). One key finding is the MM5 analysis indicating that simulations at 12 km resolution are more accurate than at 4 km, because of the scale-dependent parameterizations. Another key finding is the TOPLATS simulations indicating that a low parameter semi-distributed simulation replicates a high-parameter, fully distributed simulation with fair to good accuracy.

RELATED PUBLICATIONS

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Sharif, H. O., W. T. Crow, N. L. Miller, and E. F. Wood, Multi-decadal high-resolution land surface modeling study in the Southern Great Plains. J. of Hydrometeorology (submitted), 2005.

ACKNOWLEDGMENTS

This work was supported by the Director, Office of Science, Office of Biological and Environmental Research, Climate Change Research Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.



NEW EMISSION SCENARIOS AND CALIFORNIA CLIMATE IMPACTS: AN ANALYSIS OF EXTREME HEAT

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RESEARCH OBJECTIVES

Two global climate models, the low-sensitivity NCAR/DOE Parallel Climate Model and the medium-sensitivity UK Met Office HadCM3 model, were used to calculate climate change resulting from the B1 (lower) and A1fi (higher) emissions scenarios. These scenarios bracket a large part of the range of Intergovernmental Panel on Climate Control (IPCC) nonintervention emissions futures, with atmospheric concentrations of CO₂ reaching ~550 ppm (B1) and ~970 ppm (A1fi) by 2100. The objectives of this Extreme Heat Analysis component of the larger study (Hayhoe et al., 2004) is to quantify the change in likelihoods of extreme heat days for urban population centers, for the higher and lower emission scenarios of 2045–2054 and 2090–2099, compared to the reference period 1989–1998.

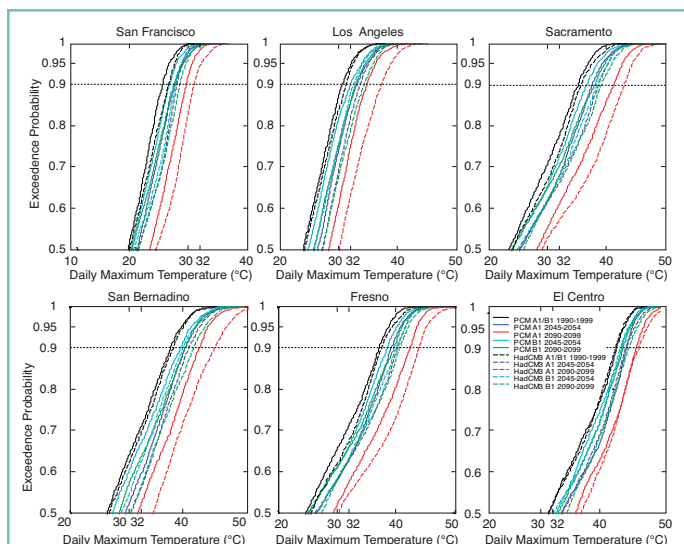


Figure 1. Temperature exceedance probabilities for PCM (dashed) and HadCM3 (solid) projections under emission scenarios A1fi (Red) and B1 (Green) for 2090–2099 for San Francisco, Los Angeles, Sacramento, San Bernadino, Fresno, and El Centro

APPROACH

Changes in local temperature extremes were evaluated based on calculated exceedance probability (EP) analyses, using the distribution of daily maximum temperatures downscaled to representative locations and ranked. Exceedance probabilities define a given temperature for which the probability exists that X% of days throughout the year will fall below that temperature. Conversely, there is a probability that (100-X)% days will lie above that threshold. For example, if the 35°C EP averages 95% for 2070–2099, an average of 95% or ~347 days per year lie below 35°C. Exceedance probabilities of daily time series have been used to indicate the likelihood

of occurrence of temperature, precipitation, and runoff (Miller et al., 2003).

ACCOMPLISHMENTS

The maximum daily temperature (Tx) EP at San Francisco, Los Angeles, Sacramento, San Bernadino, Fresno, and El Centro for emission scenarios A1fi and B1, using PCM and HadCM3, are shown in Figure 1. The 2090–2099 50% and 95% Tx EPs for San Francisco increase by more than 7°C for the HadCM3 A1FI scenario, and 6°C for the PCM A1FI scenario. The 1990–1999 baseline 95% EP becomes 58% and 70% for HadCM3 and PCM A1FI, and 86% and 78% for B1, respectively. Such shifts indicate that San Francisco's historic 5% warmest days may occur as frequently as 30–42% of the year for A1FI and 14–22% for B1, by the end of this century.

Los Angeles has a more dramatic shift. In the 2090–2099 HadCM3 and PCM B1 projections under the A1fi emission scenario, the heat threshold is exceeded by 35% and 22%, respectively. (See Figure 1). The lengthening of future heat-wave seasons results primarily from earlier onset, with the season beginning 25–40 days earlier under B1, and twice that (50–80 days earlier) under the A1fi scenario. Under A1fi, 49–83 more heat-wave days are seen, which represents an increase of ~20–30 more days than under the B1 scenario.

SIGNIFICANCE OF FINDINGS

The significance of this extreme heat analysis is the well-established link between extreme heat and excess summer mortality. A simple temperature threshold approach without acclimatization suggests that heat mortality in Los Angeles may increase by 2–4 times under B1 and 6–10 times under A1fi by the 2090s. With acclimatization, these estimates are 15–20% lower. Individuals likely to be most affected include the elderly, children, economically disadvantaged, and already ill.

RELATED PUBLICATIONS

- Hayhoe, K, D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider and others, Emissions Pathways, Climate Change, and Impacts on California. Proc. Nat'l Acad. Sci., 101, 12422–12427, 2004. Berkeley Lab Report LBNL-56119.
- Miller, N.L., K.E. Bashford, and E. Strem: Potential impacts of climate change on California hydrology. J. Amer. Water Resour. Assoc, 39, 771–784. 2003. Berkeley Lab Report LBNL-51313.

ACKNOWLEDGMENTS

This work was supported by the California Energy Commission's Climate Change Program.

THE CALIFORNIA WATER AND ENERGY SYSTEM: AN APPROACH FOR ADDRESSING FUTURE CRISES

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RESEARCH OBJECTIVES

The purpose of this fundamental-climate-science, applied-hydrology and economics project is to better understand how natural processes and human intervention interact to influence California's water supply, and the sensitivity of this system to potential disruptions.

Our research objectives are to: (1) quantify the climate drivers impacting mountain front recharge, snowmelt runoff, and net infiltration in the Sierra Nevada and Central Valley; (2) investigate the sensitivity of the water table to these inputs and to pumping with-drawals; (3) adapt existing geophysical logging and monitoring techniques for characterizing the depth distribution of groundwater contaminants; and (4) develop a regional resource management model to demonstrate economic tradeoffs between agricultural and environmental groundwater pumping, incorporating long-term aquifer degradation.

APPROACH

Our research team brings together hydroclimate science, water resources engineering, and economic analyses through drought-sensitivity simulations, groundwater-surface water response studies—at both Central Valley and Merced Basin scales—and studies of the economic impact associated with water supply limitations. Three integrated studies representing climate science, water resources, and economics are merged, resulting in a new type of multidisciplinary analysis. A schematic of this approach is given in Figure 1.

ACCOMPLISHMENTS

Our water-energy system project accomplishments have advanced around three interrelated components. The first component involved coupling climate, land surface, and groundwater models to simulate the water flux and balance. Research focused on the new coupling, testing, and simulations of the LBNL Regional Climate System Model with a state-of-the-art land-surface/shallow subsurface model (NCAR Community Land Model version 3: CLM3), an advanced groundwater-surface water coupling with CLM and the Berkeley Lab Earth Sciences Division

(ESD) TOUGH2 code, and a 104-year atmospheric-land surface simulation with a 25-year drought simulation for the Merced

River Basin Transect. The second component of our work includes salinity with depth characterization at four wetlands sites with difficult-to-access well casings, using an advanced ESD geophysical logging approach. This data has been prepared to calibrate our surface-groundwater code for the Merced Basin.

The third component includes the development of economic models for the value of water supply reliability and the value of groundwater-surface water storage. The water supply reliability model has been calibrated using regional water-source and land value data. A conceptual version of water storage model has been developed using data from the Merced Basin.

SIGNIFICANCE OF FINDINGS

The success of our water-energy system has resulted in a California Energy Commission (CEC) grant for significantly more comprehensive advances in our climate, water, and pricing models, as well

as new analyses. This project has resulted in the synthesis of hydrological simulations and economic analysis, representing a new approach for guiding water management under climate change.

RELATED PUBLICATIONS

Brekke, L.N., N.L. Miller, K.E. Bashford, N.W.T. Quinn, and J.H. Dracup, 2004: Climate Change Impacts Uncertainty for the San Joaquin River Basin. *J. Amer. Water Resources Assoc.* 40, 149-164.

ACKNOWLEDGMENTS

This work was supported by Laboratory Directed Research and Development (LDRD) funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We thank the California Energy Commission and California Department of Water Resources (CDWR) for working with us on advancing this research and developing a new drought response scenario for California policy makers.

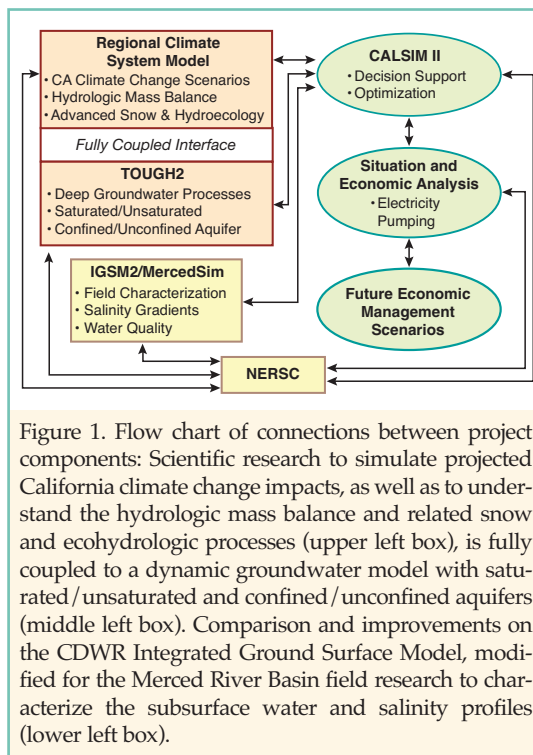


Figure 1. Flow chart of connections between project components: Scientific research to simulate projected California climate change impacts, as well as to understand the hydrologic mass balance and related snow and ecohydrologic processes (upper left box), is fully coupled to a dynamic groundwater model with saturated/unsaturated and confined/unconfined aquifers (middle left box). Comparison and improvements on the CDWR Integrated Ground Surface Model, modified for the Merced River Basin field research to characterize the subsurface water and salinity profiles (lower left box).

ANALYZING THE IMPACT OF THE THREE GORGES DAM ON LOCAL CLIMATE

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RESEARCH OBJECTIVES

The Three Gorges Dam (TGD), on the Yangtze River in China, represents the world's largest man-made reservoir, with a hydroelectric potential of 84.7 billion kilowatt hours and flood reduction in low-lying regions downstream. By 2009, the TGD is expected to fill the projected 39.3 billion m³ storage capacity. The submerged 663 km length of the Yangtze River will have a 1,040 km² wet surface area, representing a significant land-use change in topography and evaporation, which in turn is expected to cause changes in regional weather and climate patterns. Previous studies suggest that the annual average near-surface air temperature in the vicinity of the TGD will increase by 0.3°C. However, the impact on local climate resulting from the change in surface area and weather patterns has not been systematically quantified and is not fully understood.

The objectives of this sensitivity study are to determine the changes in surface characteristics within the TGD area, from one of steep, vegetated terrain to a large, flat saturated surface, with a potential evaporating rate. We investigate changes in local circulation and moisture patterns and seek to quantify the relative change in temperature, precipitation, and energy fluxes using a regional atmospheric model coupled to a land-surface model.

APPROACH

Simulations were conducted and results analyzed for the period April 2–May 16, 1990, using the nonhydrostatic version of the Penn State/National Center for Atmospheric Research (NCAR) Mesoscale Model Version 5 (MM5) coupled with the Community Land Model Version 2 (CLM2).

ACCOMPLISHMENTS

Initial analyses suggest that increased surface evaporation leads to a colder surface with decreased sensible heat flux (Figure 1a), which further cools the atmospheric column, producing stronger downdrafts of air mass and dissipation of clouds. The reduction in clouds in turn causes an increase in solar radiation (Figure 1b), countering the decrease in surface temperature. However, the increase in descending air mass appears to divert atmospheric moisture out of the region in the lower troposphere,

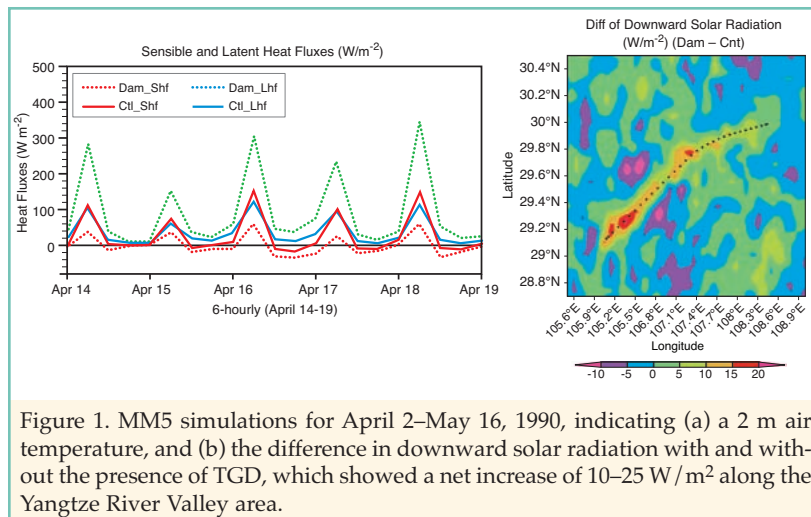


Figure 1. MM5 simulations for April 2–May 16, 1990, indicating (a) a 2 m air temperature, and (b) the difference in downward solar radiation with and without the presence of TGD, which showed a net increase of 10–25 W/m² along the Yangtze River Valley area.

which tends to reduce any precipitation enhancement resulting from the intensified surface evaporation.

SIGNIFICANCE OF FINDINGS

This preliminary examination of the mechanisms associated with local climate change in the TGD region suggests a more comprehensive study, using a fine-scale mesoscale (1 km resolution) simulation for periods up to several years, and a further analysis utilizing remote-sensed observation. The full manuscript to this initial study has been published in *Geophysical Review Letters* (Miller et al., 2005), and a second-phase, more comprehensive analysis is currently being completed by the authors of this study.

REFERENCES

Miller, N.L., J. Jin, and C.-F. Tsang, Local climate sensitivity of the Three Gorges Dam. *Geophysical Review Letters* 32, L16704, doi:10.1029/2005GRL02821, 2005. Berkeley Lab Report LBNL-58249.

ACKNOWLEDGMENTS

This work was supported by the Director, Office of Science, Office of Biological and Environmental Research, Climate Change Research Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

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RESEARCH OBJECTIVES

The goal of the West Coast Regional Carbon Sequestration Partnership (WESTCARB) is to address several key issues that impact the development of practical, commercially ready sequestration technologies. WESTCARB is one of seven partnerships established by the DOE to evaluate carbon dioxide capture, transport, and sequestration (CCS) technologies best suited for different regions of the country. WESTCARB is evaluating both terrestrial and geologic sequestration options for the region comprising Arizona, California, Nevada, Oregon, Washington, Alaska, and British Columbia.

APPROACH

WESTCARB is carrying out five major tasks: (1) collecting data to characterize major CO₂ point sources, the transportation options, and the terrestrial and geologic sinks in the region; (2) addressing key issues affecting deployment of CCS technologies; (3) conducting public outreach and education work; (4) integrating and analyzing data to develop supply curves and cost-effective sequestration options; and (5) identifying appropriate terrestrial and geologic demonstration projects in the region. WESTCARB has assembled a diverse consortium of nearly 50 participants, including state natural resource, environmental protection, and other agencies; national labs and universities; private companies working on CO₂ capture, transportation, and storage technologies; nonprofit organizations; commercial users of CO₂, such as the oil and gas industry; policy/governance coordinating organizations; and others.

ACCOMPLISHMENTS

Data on 81 major point sources, which account for more than 75% of the CO₂ emissions in the region, have been compiled and organized into a geographic information system (GIS) database, which is maintained at the Utah Advanced Geographic Reference Center. The WESTCARB geologic sink GIS database contains data on the significant sedimentary basins in the region. In California, screening of 104 sedimentary basins excluded 77 on the basis of insufficient depth (<800 m), lack of seals, or lack of access. The estimate of the storage capacity of saline formations in the ten largest remaining basins ranged from 146 to 840 Gt CO₂, depending on assumptions about what fraction of the formations is used, what fraction of the pore volume is filled with separate-phase CO₂, and salinity. The amount of CO₂ that could be stored in oil reservoirs associated with EOR was found to be 3.4 Gt. If existing

plants are retrofitted for capture, about 50 M tons of CO₂ per year could be sequestered for \$35 per ton CO₂ avoided.

Terrestrial sequestration studies are using GIS databases to characterize the carbon baseline in the region and to develop supply curves for major classes of land use. Analysis of changes in carbon stocks in California for the decade of the 1990s revealed that forests and rangelands were responsible for a net removal of carbon dioxide from the atmosphere of 7.55 MMTCO₂eq/yr, and that agricultural lands were responsible for a net emission of 0.35 MMTCO₂eq/yr. In California, it was found that rangeland conversion yielded the greatest carbon benefits. For an afforestation project of 80 years duration, it was found that 5.6 GT of carbon could be stored at less than \$50/MT C, involving an area of about 21 million acres.

Storage site permitting, monitoring, and injection regulations, as well as health, safety, and environmental (HSE) risks, are key issues affecting the deployment of geologic sequestration technologies. A screening-level risk assessment tool has been developed to help select sites with minimum HSE risk. The regulatory framework in each state has been defined as a first step in addressing regulatory issues. These issues are also being addressed through public outreach efforts.

SIGNIFICANCE OF FINDINGS

Though analyses are continuing in several WESTCARB states, results to date show that significant sequestration opportunities are available in the region. In California, the Central Valley, alone, has capacity for several hundred years of CO₂ emissions from utilities. Because of its capacity, and the presence of oil and gas reservoirs, the Central Valley also is favored as a location for field pilot studies. Terrestrial sequestration opportunities have been identified in afforestation and forest fire mitigation. Though smaller in magnitude than the geologic opportunities, the terrestrial opportunities are much less expensive.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Fossil Energy, Office of Coal and Power Systems, of the U. S. Department of Energy through the National Energy Technology Laboratory, under DOE Cooperative Agreement No. DE-FC26-03NT41984, and DOE Contract No. DE-AC03-76SF00098, and by the California Energy Commission through Work Authorization Contract #500-02-014, Work Authorization #MR-021, and Interagency Agreement 500-03-018.

SCREENING AND RANKING FRAMEWORK FOR GEOLOGIC CO₂ STORAGE

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RESEARCH OBJECTIVES

The injection of CO₂ into deep geologic formations for geologic CO₂ storage involves the risk that CO₂ will leak from the target formation to the near-surface environment. Once in the near-surface environment, CO₂ can cause detrimental health, safety, and environmental (HSE) effects. One consideration in the selection of geologic CO₂ storage sites is the minimization of potential HSE risks. The objective of this work is to develop a screening and ranking framework (SRF) to evaluate the relative risk that CO₂ will leak to the near-surface environment and cause HSE effects. The SRF is designed so that it can be applied to sites with limited data as appropriate for pilot studies. The expected users of the SRF are geoscientists or hydrologists with access to limited published information about the site in reference books or maps. In short, the framework is designed to answer the question, "From a choice of several potential sites, which site has the lowest HSE risk?"

APPROACH

The approach stems from the realization that HSE risk is related to three fundamental characteristics of a geologic carbon storage site:

1. Potential of the target formation for long-term containment of CO₂
2. Potential for secondary containment, should the primary target site leak
3. Potential of the site to attenuate and/or disperse leaking CO₂, should the primary formation leak and secondary containment fail

The SRF tool is designed to provide a qualitative and independent assessment of each of these three characteristics, through a numerical evaluation of properties/values associated with various attributes of the three general characteristics. For example, three attributes of the potential for the target formation to contain CO₂ for long periods are (1) the nature of the primary seal, (2) the depth of the reservoir, and (3) the properties of the reservoir. The properties of the primary seal attribute are thickness, lithology, demonstrated sealing capacity, and lateral continuity. Similar

properties for all of the other attributes are listed in the spreadsheet. The user simply assigns numerical values to these attributes, based on suggestions in the spreadsheet. In addition, the

user must assign weights and uncertainties to the properties, which are carried along to the final display. The results are summarized and displayed graphically in the summary worksheet, one graphic from which is shown in Figure 1.

ACCOMPLISHMENTS

An HSE screening and ranking framework has been developed, based on the three fundamental characteristics of a CO₂ sequestration site. The system allows the user to arbitrarily weight and assign uncertainty to the properties associated with the attributes of the fundamental characteristics,

to evaluate and rank two or more sites relative to each other. We emphasize that the SRF tool is intended to guide the selection of the most promising sites, for which more detailed risk assessment would be carried out. Testing and further development of the SR framework are under way.

SIGNIFICANCE OF FINDINGS

The SRF shows that comparative evaluations of prospective sites with limited characterization data can be accomplished, and that the ranking offers a way of screening sites based on potential for CO₂ leakage and seepage, as well as related HSE risk.

RELATED PUBLICATION

Oldenburg, C.M., HSE screening risk assessment (SRA) for geologic CO₂ sequestration. Fourth Annual Conference on Carbon Capture and Sequestration, Alexandria, Virginia, May 2-5, 2005. Berkeley Lab Report LBNL-57280.

ACKNOWLEDGMENTS

This work was supported in part by WESTCARB through the Assistant Secretary for Fossil Energy, Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL), and Lawrence Berkeley National Laboratory, under Department of Energy Contract No. DE-AC03-76SF00098.

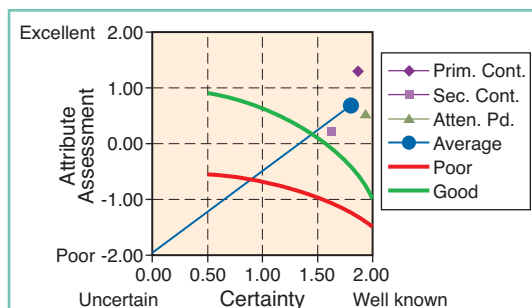


Figure 1. Summary graphic showing the attribute assessment (y-axis) and uncertainty (x-axis) of the three fundamental characteristics along with qualitative regions of "poor," "fair," and "good" HSE risk for the Rio Vista gas field

NEAR-SURFACE CO₂ LEAKAGE MIGRATION

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RESEARCH OBJECTIVES

The ultimate failure of geologic CO₂ storage is the seepage of injected CO₂ out of the ground surface into the atmosphere, with associated potential health, safety, and environmental (HSE) risks. To evaluate (1) potential HSE risks, (2) near-surface monitoring strategies for CO₂ storage verification, and (3) the effectiveness of geologic CO₂ storage even in leaky systems, we must understand the behavior of leaking CO₂ in the near-surface environment. The objective of this research is to study CO₂ migration in the near surface environment by numerical simulation and theoretical analyses. The near-surface environment relevant to our studies is approximately ± 10 m from the ground surface and includes porous media (e.g., sediments, fractured rock, and soils), surface water (e.g., lakes, rivers, estuaries, and shallow marine environments), and the lower part of the atmospheric surface layer. We define leakage as CO₂ migration in the subsurface away from the primary target formation, while seepage is CO₂ migration across an interface, such as the ground surface or the basement wall of a building.

approach is to model simple systems with variable properties to cover a range of natural conditions. The domain for the simulations is a radial 30 m thick vadose zone with a constant leakage flux specified at the bottom and a surface rainfall infiltration recharge of 10 cm/yr.

ACCOMPLISHMENTS

Shown in Figure 1 are the near-surface fluxes and concentrations for three different leakage fluxes and a variety of system properties. As shown in Figure 1, seepage flux and concentration are most sensitive to the strength of the leakage source. Note that concentrations can be quite large even for fluxes that are not much larger than a typical biological flux. From our theoretical studies of CO₂ entry into surface water, we found that ebullition and bubble flow will be the dominant form of transport of CO₂ leakage in shallow surface water.

SIGNIFICANCE OF FINDINGS

The finding that small fluxes can lead to relatively large CO₂ concentrations in the shallow subsurface points to the utility of monitoring the subsurface for anomalous CO₂ concentrations. As for surface water, ebullition appears to be the expected process, making seepage detection in surface water relatively simple because bubbles are easy to detect by visual and acoustic methods. Our results suggest that once CO₂ is in the near-surface environment, it will tend to seep to the atmosphere. If seepage fluxes are small, integrated measurement and modeling strategies will be needed for CO₂ storage verification, in order to discern weak leakage and seepage signals from natural background variability.

RELATED PUBLICATIONS

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ACKNOWLEDGMENTS

This work was supported by the Office of Science, U.S. Department of Energy under Contract No. DE-AC03-76SF00098, and by a Cooperative Research and Development Agreement (CRADA) between BP Corporation North America, as part of the CO₂ Capture Project (CCP) of the Joint Industry Program (JIP), and the U.S. Department of Energy through the National Energy Technologies Laboratory (NETL).

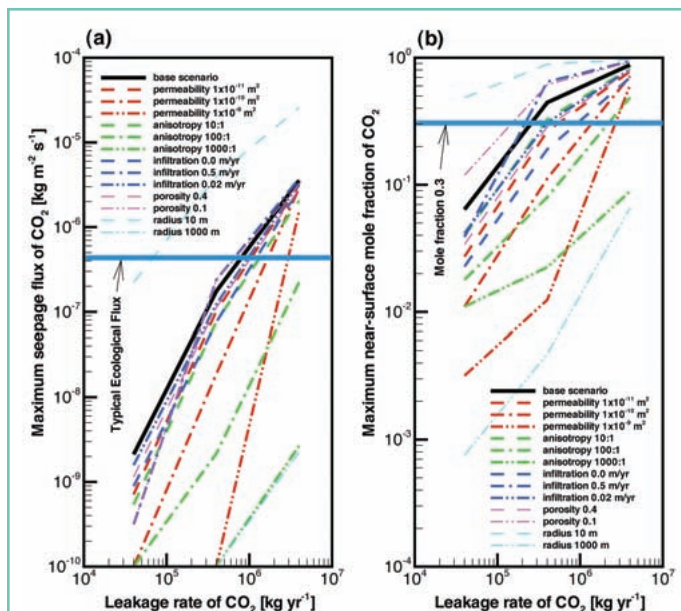


Figure 1. (a) Maximum seepage flux of CO₂ and (b) near-surface gas-phase mole fraction of CO₂ as a function of leakage rate at steady-state seepage conditions for three leakage fluxes and a variety of vadose zone properties.

APPROACH

We have developed and applied T2CA, a TOUGH2 module for simulating CO₂ and air in the near-surface environment. In addition, we have used solubility models and related theoretical analyses of ebullition potential of CO₂ in NaCl brines to evaluate the process of CO₂ entering surface water from below. Our

SELF-ENHANCING AND SELF-LIMITING EFFECTS DURING CO₂ LEAKAGE FROM GEOLOGIC DISPOSAL RESERVOIRS

Karsten Pruess

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RESEARCH OBJECTIVES

The amounts of CO₂ that would have to be stored in geologic reservoirs are very large, and it appears inevitable that such plumes would encounter imperfections in the caprock, causing leakage. This raises a concern over whether it may be possible for a CO₂ leak to be self-enhancing, in such a way as to give rise to run-away discharge at the land surface with potentially serious consequences. CO₂ has physical properties—including lower density, much lower viscosity, and higher compressibility than aqueous fluids—which suggest that such a possibility should be taken seriously. The purpose of this research is to explore the behavior of leaking CO₂, and to identify conditions, if any, in which CO₂ could be discharged at the land surface in an eruptive manner.

APPROACH

Using information from natural systems, including CO₂ degassing in volcanic areas, and hydrothermal and pneumatic eruptions, we attempt to identify hydrogeologic conditions that would facilitate CO₂ discharge. Numerical simulations using our general-purpose simulator TOUGH2 and a special fluid property module for water-CO₂ mixtures were performed to study the behavior of proposed leakage systems that may involve supercritical as well as gaseous and liquid CO₂.

ACCOMPLISHMENTS

A 1 m thick vertical fault was prepared with initial conditions typical for continental crust (land surface conditions of 15°C temperature and 1 bar pressure; geothermal gradient of 30°C/km and hydrostatic pressures). Carbon dioxide was then introduced at a constant overpressure of approximately 9.5 bar relative to hydrostatic at a depth of 710 m. The CO₂ flows upward and outward from the injection point, displacing most of the water. Substantial cooling effects are observed as the CO₂ rises, caused by decompression and boiling of liquid CO₂ into gas. The interplay between multiphase flow and heat-transfer effects causes nonmonotonic discharge behavior at the land surface (see Figure 1). The strong feedback between fluid flow and heat transfer tends to limit CO₂ fluxes, gives rise to quasi-periodic variations in flow rates, and makes it difficult to envision scenarios in which leakage of CO₂ as a free phase could develop a self-enhancing runaway discharge at the land surface.

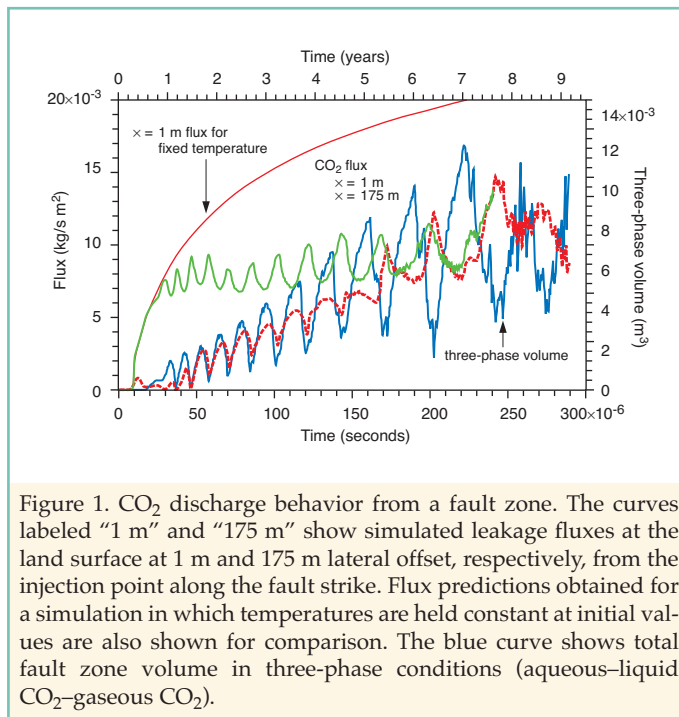


Figure 1. CO₂ discharge behavior from a fault zone. The curves labeled "1 m" and "175 m" show simulated leakage fluxes at the land surface at 1 m and 175 m lateral offset, respectively, from the injection point along the fault strike. Flux predictions obtained for a simulation in which temperatures are held constant at initial values are also shown for comparison. The blue curve shows total fault zone volume in three-phase conditions (aqueous-liquid CO₂-gaseous CO₂).

SIGNIFICANCE OF FINDINGS

Leakage of CO₂ along a fault or fracture zone is accompanied by strong cooling effects. These effects limit CO₂ discharge rates and give rise to nonmonotonic leakage behavior.

RELATED PUBLICATION

Pruess, K., Numerical studies of fluid leakage from a geologic disposal reservoir for CO₂ show self-limiting feedback between fluid flow and heat transfer. *Geophys. Res. Lett.*, 32 (14), L14404, doi:10.1029/2005GL023250, 2005. Berkeley Lab Report LBNL-57362.

ACKNOWLEDGMENTS

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SPATIALLY DISTRIBUTED CO₂, SENSIBLE HEAT, AND LATENT HEAT FLUXES OVER THE SOUTHERN GREAT PLAINS

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RESEARCH OBJECTIVES

We have developed a method to estimate regional-scale ecosystem CO₂ and energy exchanges at the Atmospheric Radiation Measurement Southern Great Plains (ARM-SGP) facility. This work addresses U.S. national goals of estimating regional CO₂ sources and sinks, and provides inputs to forward and inverse models.

APPROACH

Our method incorporates meteorological data from over 120 Oklahoma and Kansas Mesonet sites into a distributed land surface model (ISOLSM [Cooley et al., 2005; Riley, 2005; Riley et al., 2002], which is based on LSM1.0) of fluxes between ecosystems and the atmosphere. In addition to CO₂ and energy exchanges, ISOLSM predicts fluxes and pools of ¹⁸O in CO₂ and H₂O and ¹³C in CO₂. The meteorological datasets, compiled by ARM, contain fields for precipitation, radiation, wind speed, air temperature, and atmospheric pressure. Our interpolation provides meteorological input for ISOLSM at user-specified resolution across the ARM domain.

We modified the land surface (vegetation) types in ISOLSM to correspond to the dominant land covers in the domain. Soil hydraulic characteristics are determined from the USGS STATSGO 1 km resolution soil map. We have tested ISOLSM in the dominant crop (winter wheat) in the SGP region [Riley et al., 2003] and calibrated to the dominant vegetation types with measurements made by portable 4 m systems comprised of a sonic anemometer and an open-path infrared gas analyzer (<http://www.arm.gov/instruments/carbon.stm>). Our preliminary calibration was accomplished by manipulating the maximum carboxylation rate and soil-organic-matter content associated with each vegetation type. Future work will improve on this approach by statistically minimizing errors in net ecosystem exchange (NEE) with these and other parameters.

ACCOMPLISHMENTS

Our results show that the interpolated meteorological fields are in good agreement with independent measurements in the area's dominant vegetation types. The bottom panel shows predicted and measured net CO₂ fluxes in a wheat field. Excellent agreement was also obtained for two other portable eddy flux sites (in pasture and sorghum fields).

SIGNIFICANCE OF FINDINGS

Typical midday NEE variations across the ARM-SGP domain can be large (up to 25 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (top panel), implying that estimating regional NEE requires accurate characterization of spatial

heterogeneity in vegetation characteristics and meteorological forcing. Currently, the region is typically modeled as homogeneous cropland. Our approach allows us to quantify uncertainty in regional flux estimates associated with uncertainties in vegetation type, soil types, and spatial and temporal scaling of surface characterization and meteorological forcing. This work will benefit both "bottom-up" and "top-down" approaches to quantifying regional-scale surface CO₂ and energy exchanges.

RELATED PUBLICATIONS

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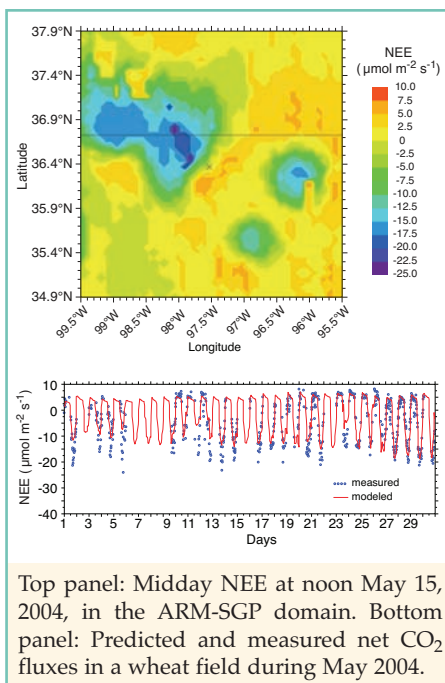
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ACKNOWLEDGMENTS

This work was supported by the Director, Office of Science, Office of Biological and Environmental Research, Climate Change Research Division, Atmospheric and Radiation Measurements Program, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.



MULTI-DECADAL HIGH-RESOLUTION HYDROLOGIC MODELING OF THE ARKANSAS-RED RIVER BASIN

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RESEARCH OBJECTIVES

This follow-on study of the DOE Water Cycle Pilot (Miller et al. 2005) evaluates the contrast between fine spatial scales at which heterogeneity is significant (1 km and finer) and coarser scales at which climate simulations are generated. The objectives of this study are to identify physiographic and climatic controls on the spatial variability of soil moisture; to develop new subgrid parameterizations for soil moisture during wet and dry conditions; to examine the spatial scaling properties of soil moisture; and to perform a statistical analysis of the teleconnections between climatic variables and land surface states and processes, such as soil moisture and evapotranspiration.

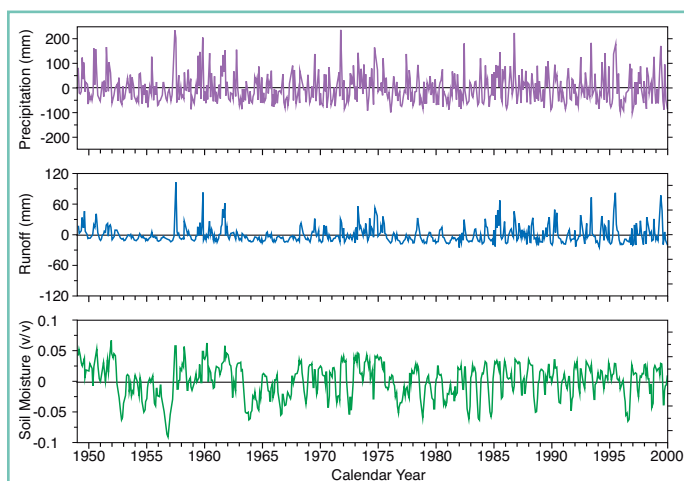


Figure 1. Time series of monthly anomalies of precipitation, runoff, and soil water storage. Notice that while runoff amplifies positive anomalies in precipitation, soil water storage amplifies negative anomalies.

APPROACH

We generated a 51-year simulation of water and energy fluxes over the Arkansas-Red River Basin, using the fully distributed land surface model, TOPLATS, at fine temporal (hourly) and spatial (1 sq. km) resolutions, to bridge the gap between traditional hydrologic modeling and regional land-surface modeling. We focused on the accuracy of streamflow simulations at the sub-basin scale, with physically based descriptions of heat and water exchange at the land-atmosphere interface, because sub-basin scale biases may grow nonlinearly over time, leading to larger basin-scale biases.

ACCOMPLISHMENTS

The surface runoff did not show a distinct shift of the east-west gradient during the summer months as observed for precipitation. The variability of interannual basin-averaged precipitation varied strongly and decreased during the simulation period. Results indicate that precipitation variability amplified in the runoff, but decreased with time. Both basin-averaged precipitation and surface runoff increased during the simulation period, on average, at different rates, suggesting that evapotranspiration increased. This conclusion is supported by analysis of evapotranspiration at the sub-basin scale and observed discharge. Results agree with mounting evidence of an accelerating hydrologic cycle over the conterminous United States. Monthly precipitation and runoff have also increased over the simulation period, except during May and July. It was also found that runoff amplifies positive precipitation anomalies, while soil water storage amplifies negative anomalies.

SIGNIFICANCE OF FINDINGS

The study enhances understanding of the correlation between mean-monthly, seasonal, and annual variations in surface energy fluxes, soil moisture, and stream flow and large-scale atmospheric patterns. The results of this analysis will help clarify the sources of long-term hydrologic variability at regional scales.

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ACKNOWLEDGMENTS

This work was partially funded by the DOE Water Cycle Pilot and a National Oceanic and Atmospheric Administration (NOAA) grant through the Cooperative Institute for Climate Science at Princeton University.

A NONITERATIVE MODEL FOR CO₂-H₂O MUTUAL SOLUBILITIES IN CHLORIDE BRINES

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RESEARCH OBJECTIVES

The objective of this study was to develop a numerically efficient model to compute the mutual solubilities of CO₂ and H₂O in chloride brines, for applications to CO₂ geologic sequestration studies. One specific goal was to avoid degrading the performance of numerical fluid-flow simulations when using such a model.

APPROACH

We previously developed a numerically efficient thermodynamic model for phase partitioning without salt effects. This model was shown to provide an excellent match to experimental

data in the range 12–100°C and up to 600 bar. Here, the model is extended to NaCl and CaCl₂ solutions by including an activity coefficient for aqueous CO₂, and taking the activity of water as its mole fraction on the basis of a fully ionized salt. Several published activity coefficient formulations were evaluated, two of them based on a Pitzer formulation and providing best results (Figure 1).

ACCOMPLISHMENTS

For solutions up to 6 molal NaCl and 4 molal CaCl₂ (Figure 1), the best activity coefficient formulations yield calculated CO₂ solubilities within less than 7% (root-mean-square error) of experimental data. Thus, the new model allows computing mutual solubilities in a noniterative manner and with an accuracy typically within experimental uncertainty.

SIGNIFICANCE OF FINDINGS

Previously published models involve complex correlations requiring an iterative solution and/or do not cover temperatures below ~100°C at high pressures. The approach followed here is noniterative, thus numerically efficient, and reproduces experimental solubilities with sufficient accuracy for the study of geologic CO₂ disposal.

RELATED PUBLICATIONS

Spycher, N., K. Pruess, and J. Ennis-King, CO₂-H₂O mixtures in the geological sequestration of CO₂. I. Assessment and calculation of mutual solubilities from 12 to 100°C and up to 600 bar. *Geochimica et Cosmochimica Acta*, 67, 3015–3031, 2003. Berkeley Lab Report LBNL-50991.

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ACKNOWLEDGMENTS

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, Division of Chemical Sciences, Geosciences, and Biosciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

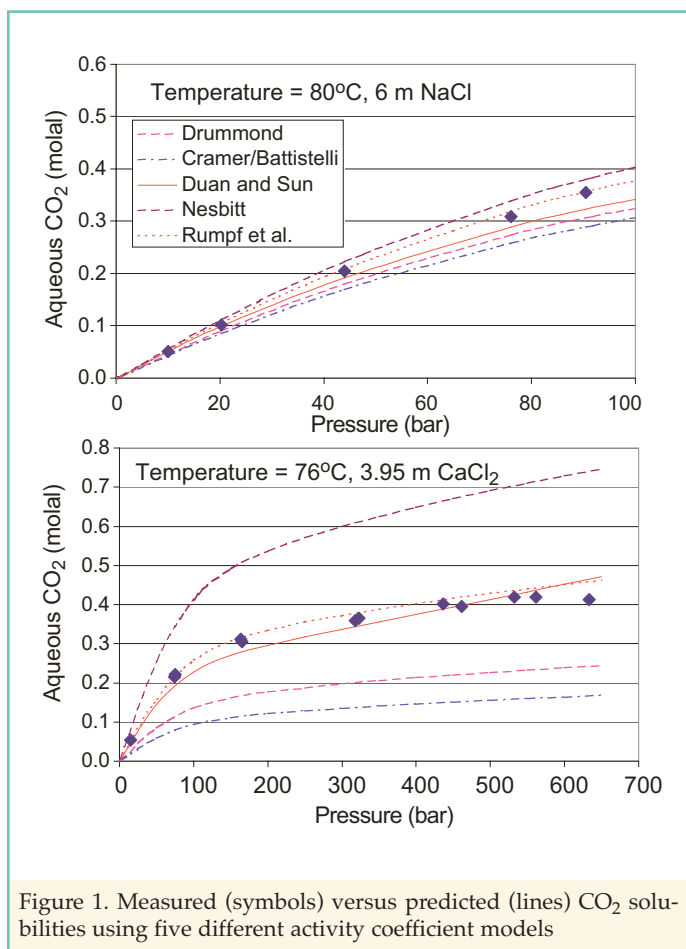


Figure 1. Measured (symbols) versus predicted (lines) CO₂ solubilities using five different activity coefficient models

CARBON CYCLING IN THE SOUTHERN GREAT PLAINS: THE ARM/LBNL CARBON PROJECT

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RESEARCH OBJECTIVES

The DOE Atmospheric and Radiation Measurement (ARM)/Berkeley Lab Carbon Project is making a coordinated suite of carbon concentration, isotope, and flux measurements to support a range of scaling and integration exercises, including those proposed for the North American Carbon Program:

- Quantifying regional atmospheric CO₂ sources and sinks
- Developing land-surface models and testing carbon exchange parameters
- Predicting the effect of land use and climate on carbon and energy fluxes
- Testing innovative methods for inferring carbon fluxes

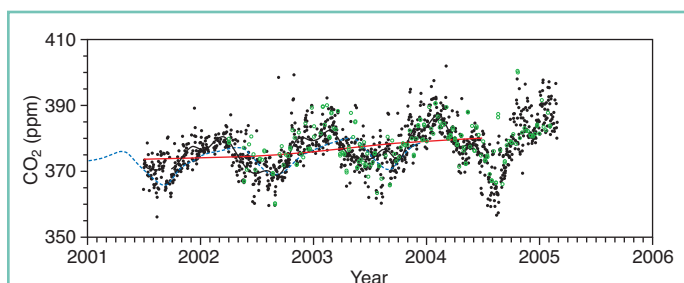


Figure 1. Precise atmospheric CO₂ concentrations (black circles) measured at 60 m, during well-mixed, afternoon conditions (14:00–17:00 CST daily). The running average (black line) shows the seasonal cycle amplitude at ~15 ppm, with a minimum at the peak N Hemisphere growing season, rather than peak local growing season in late spring. The average annual trend in ARM data (red line) matches the NOAA network trend for the SGP latitude band (dashed line). The NOAA flasks were collected ~14:30 CST weekly.

APPROACH

We are working in the ARM Southern Great Plains test bed, a 300 × 300 km area of Oklahoma and Kansas. Most of our carbon measurements are collected at the 60 m tower of the ARM Central Facility, including precise CO₂ concentration profiles, carbon eddy covariance fluxes, National Oceanic and Atmospheric Administration (NOAA) flasks in the mixed layer and free troposphere (by aircraft), and diurnal profiles of ¹³C and ¹⁸O in CO₂. The precise CO₂ measurements and NOAA flasks tie the ARM site to the global atmospheric network. This year, we have added continuous CO measurements and are in the process of adding continuous airborne CO₂ and ¹⁴CO₂ flask sampling to assist with source attribution.

ACCOMPLISHMENTS

By comparing airborne and tower data, we have found that the 60 m tower is tall enough to sample well-mixed boundary-layer air during the afternoon, when convective mixing is active. As a

result, our data can be used to estimate regional CO₂ levels. Figure 1 shows daily CO₂ concentrations measured in the afternoon during well-mixed conditions. The annual increase over three years was more than 2 ppm y⁻¹. This trend nearly matches the global background trend (2.3 ppm y⁻¹) reported by NOAA at Mauna Loa.

Using multiple eddy flux towers, we find large heterogeneity in surface fluxes among replicate wheat fields and even larger variability between different cover types. These findings reinforce the need for model parameters that accurately represent heterogeneity in land use, to replace the typical application of a single parameter set for all crop types. We have begun testing distributed ecosystem model predictions against the eddy flux measurements, and plan to compare the distributed model results with atmospheric inversion results for estimating mesoscale carbon fluxes.

SIGNIFICANCE OF FINDINGS

As shown in Figure 1, global atmospheric CO₂ concentrations are rising rapidly. The rate of increase is the difference between anthropogenic emissions and uptake by land and oceans. The ability to predict or manage future CO₂ concentrations, and thus climate itself, depends on our ability to understand and predict terrestrial carbon exchanges. Our research at ARM addresses this need by quantifying subcontinental-scale ecosystem-atmosphere fluxes, and predicting the effects of land use and climate on atmospheric CO₂ concentrations.

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RELATED WEB SITE

ARM Carbon Web Site: <http://esd.lbl.gov/ARMCarbon/>

ACKNOWLEDGMENTS

This work was supported by the Director, Office of Science, Office of Biological and Environmental Research, Climate Change Research Division, Atmospheric and Radiation Measurements Program, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

SOIL ORGANIC MATTER AND ROOT TURNOVER: THE ENRICHED BACKGROUND ISOTOPE STUDY

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RESEARCH OBJECTIVES

In the summer of 1999 there was a large atmospheric release of $^{14}\text{CO}_2$ near the Oak Ridge Reservation (ORR), Tennessee, presumably from a local incinerator. The rapid photosynthetic uptake of the $^{14}\text{CO}_2$ created a pulse label for studying carbon (C) cycling through the ORR forests. As part of a team from four DOE labs and UC Irvine, we are utilizing this whole-ecosystem isotopic label to study, and improve modeling of, processes in terrestrial carbon cycling. At Berkeley Lab, we are investigating (1) soil organic matter (SOM) dynamics, (2) the longevity of fine roots, and (3) leaf versus root inputs to SOM.

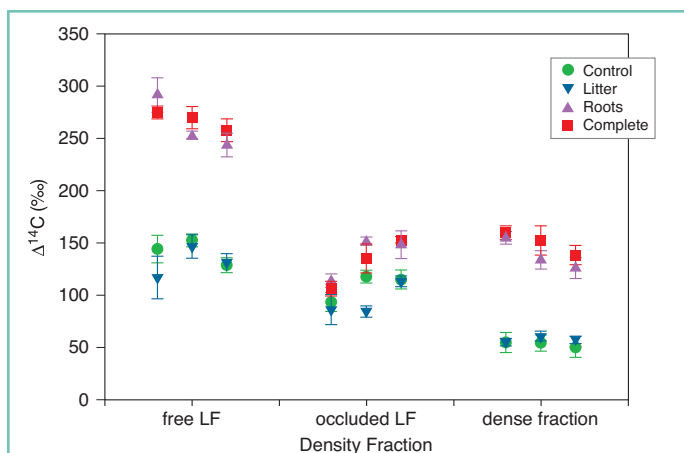


Figure 1. The radiocarbon content of SOM fractions from 0–15 cm depth at the Ultisol EBIS sites. The treatments are named for the source of elevated ^{14}C to the soil: roots, leaf litter, enriched leaves and roots (complete) or no enriched plant inputs (control). The three repeated symbols for each treatment and fraction are for the three years of sampling, 2001–2003.

APPROACH

The ORR team used a reciprocal transplant of enriched and near-background leaf litter to create four treatments, depending on type of plant ^{14}C inputs to soil: roots, leaf litter, both, or neither (no enrichment). We used a simple density fractionation method to separate SOM into interaggregate particulate organic matter (free light fraction), particulate organic matter occluded within aggregates (occluded light fraction), and organic matter complexed with minerals to form a dense fraction. We determined fine-root longevity by tracking the radiocarbon label in live and dead root populations. For fungal dynamics, ectomycorrhizae were hand-picked from freshly harvested roots. For microbial biomass, chloroform fumigation-extracts of soils were freeze-dried and combusted for graphitization. Radiocarbon content was measured at Lawrence Livermore National Laboratory by accelerator mass spectrometry. As a guide to interpreting the

results, the more ^{14}C -depleted a sample, the slower its rate of input or turnover in the ecosystem.

ACCOMPLISHMENTS AND SIGNIFICANCE

The $\Delta^{14}\text{C}$ values of the SOM fractions reveal two important aspects of carbon cycling in these forest soils. First, considering only the control treatment, the mineral-associated (dense fraction) carbon is the most depleted in ^{14}C , showing that this fraction has the slowest turnover time, while the free light fraction is the fastest cycling. The depleted signature (and thus slow turnover time) of the occluded light fraction was unexpected, because it is chemically similar to the free light fraction. These results mean that the dominant mechanisms of carbon stabilization were interaction with minerals and physical protection by occlusion, rather than intrinsic recalcitrance of the organic matter.

Second, only the soils receiving elevated ^{14}C from roots (roots and complete treatments) become enriched, and in fact there is no significant difference between control and litter soils, showing that only root inputs are contributing to SOM. The importance of root inputs relative to leaf litter was also seen in the results for ectomycorrhizal fungi and total microbial biomass. These results directly contradict the predominant assumption that litterfall is the main source of soil carbon, and its corollary that carbon inputs to soil can be approximated by litterfall rates.

The Enriched Background Isotope Study (EBIS) data are used to improve models of soil C cycling. For example, in the root study, new roots grew from a mixture of recent photosynthate and 10–20% stored reserves from the previous year. These findings are helping us parameterize a root model and estimate fine-root turnover based on trends in atmospheric $^{14}\text{CO}_2$.

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ACKNOWLEDGMENTS

This work was supported by the Office of Science, Office of Biological and Environmental Research, U.S. Department of Energy under Contract No. DE-AC03-76SF00098. EBIS is led by Paul Hanson, Oak Ridge National Laboratory.



THE IMPORTANCE OF BELOWGROUND PLANT ALLOCATION FOR TERRESTRIAL CARBON SEQUESTRATION AND CLIMATE FEEDBACKS

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RESEARCH OBJECTIVES

Soil organic matter (SOM) plays a central role in the carbon (C) cycle, by sequestering atmospheric carbon and by forming a feedback to climate change. The long turnover time of SOM compared to most plant tissues means that soils are a more efficient storage pool for C (i.e., more sequestration per unit net primary productivity [NPP]), with less interannual variability or disturbance-driven losses. We are conducting research to fill critical gaps in understanding of belowground carbon cycling in temperate forests, by quantifying:

- The lifetime of fine roots and its effect on belowground NPP
- Decomposition of root versus needles/leaves
- Total residence time of belowground C, including SOM
- Resource constraints on plant allocation

APPROACH

When plants allocate C belowground, the C cascades through several reservoirs—live roots, dead roots, microbial biomass, and humic organic matter—each with their own residence time and respiratory losses (Figure 1). A longer residence time results in more storage per unit C input. To predict C sequestration or the potential for ecosystem feedbacks to climate change, we need to understand the turnover times of C in each soil carbon pool, the pathways of C movement among pools, and the potential feedbacks to productivity.

Accordingly, we have conducted field isotope-based experiments, including (1) natural abundance ^{14}C , to determine fine-root lifetimes; (2) litterbags and *in situ* incubations of ^{13}C -labeled litter, to estimate litter decay rates; and (3) ^{13}C -labeled litter, to track root and needle decay into soil-respired CO_2 , microbial biomass, and soil organic fractions. The accomplishments represent work in ponderosa pine, mixed conifer-deciduous hardwood, and Norway spruce forests.

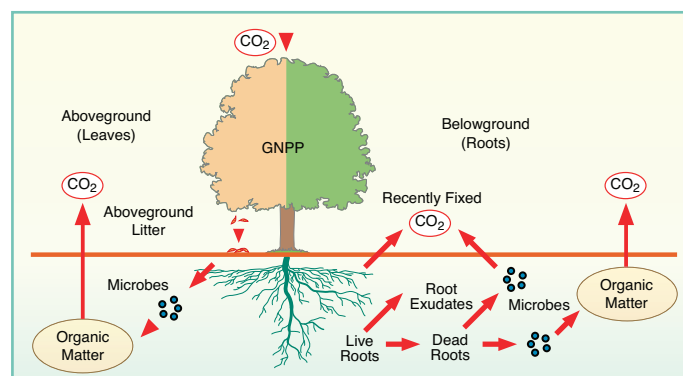
ACCOMPLISHMENTS

We find that fine roots live 2–5 years, longer than the historical assumption of annual turnover. The main implication of longer root life spans is that belowground NPP currently may be overestimated. We have begun modeling to produce better estimates of root turnover and NPP allocation. For decomposition, our experiments provide multiple lines of evidence that roots decay more slowly than needles or leaves, and there are differences in the microbial communities mediating decomposition of the tissues. For SOM, we have documented the importance of depth and mineralogy in long-term carbon storage. We have published eight peer-reviewed articles, presented

at a dozen venues, and supported two post docs, one Ph.D. student, and more than 10 undergraduates.

SIGNIFICANCE OF FINDINGS

Our results to date imply that the same amount of primary productivity leads to more C storage if it is allocated to fine roots rather than to leaves or needles in these temperate forests. Translating these results to a sequestration strategy or analysis of feedbacks poses challenges that we are addressing in the second phase of our research. It appears from our early results that plant allocation patterns influence the plant's ability to acquire and use belowground and aboveground resources, which may in turn feed back to shape productivity and long-term C sequestration.



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ACKNOWLEDGMENTS

This work was supported by the Director, Office of Science, Office of Biological and Environmental Research, under U.S. Department of Energy Contract No. DE-AC03-76SF00098. We appreciate the access and samples provided by UC Blodgett Experimental Forest, California; Harvard Forest, Massachusetts; and Hooshang Majdi, Sweden.